OTC-29557-MS

# Application of the Findings of the PISA Joint Industry Project in the Design of Monopile Foundations for a North Sea Wind Farm

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This paper was prepared for presentation at the Offshore Technology Conference held in Houston, Texas, USA, 6 – 9 May 2019.

## Abstract

Monopiles are the most common foundation type in the offshore wind industry. Their design is largely dependent on the ability to accurately model the soil-structure response of the foundation, with more refined modelling approaches enabling significant reductions in required embedment depth, fabrication cost and installation risk. The PISA joint industry project (JIP) has been completed in recent years with the objectives of developing a more refined soil-structure response modelling method compared to other available methods such as the API p-y curve approach. The scope of this paper is to detail how the PISA recommendations have been implemented on a real offshore wind farm project located in the UK North Sea, identifying how the findings can be incorporated into a combined geotechnical and structural analysis approach to enable efficient serial design of multiple foundations for wind turbines.

The paper presents how existing design processes and criteria can be modified to take into account the recommendations of the PISA JIP for use in design. Discussion will be provided on the following procedures: calibration of the PISA 1-D soil response formulations to site specific conditions; the combination of the homogeneous sand and clay formulations to accurately model soil-structure response in layered soil profiles; and, consideration of the effects of cyclic loading in conjunction with the use of the PISA monotonic soil response formulations.

Results will be presented to demonstrate the calibration of the PISA 1-D soil response formulations to a layered soil site. Discussion will also be provided on the significant monopile lengths savings achieved when using a PISA approach compared to an API p-y curve approach. The monopile mass reduction will be illustrated against trends derived from installed monopiles. Observations will be provided on how the use of a PISA based approach can affect the governing design cases and how this is likely to impact on monopile design for future projects. Discussions and conclusions will also be presented on the challenges of implementing the PISA recommendations in monopile design for real projects and what additional work is required to enable further costs savings in implementing the new design approach.

The PISA JIP recommendations are the cutting edge in monopile foundation design. The paper will provide discussion on how these recommendations can be effectively implemented in design based on experience from the foundation design for a real offshore wind farm. The wind farm in question will be one

of the first constructed for which foundations have been designed using a PISA based method, demonstrating the significant CAPEX savings possible using the PISA approach.

## Introduction

Offshore wind is the most scalable of the renewable technologies and has a major role to play in decarbonising energy infrastructure and helping mitigate climate change. In Europe the installed and operational capacity was around 15.8GW at the end of 2017 (Wind Europe, 2018) and there are ambitious growth targets to 2030. The increase in offshore wind capacity has been supported by a dramatic reduction of the levelised cost of energy. For example in the United Kingdom, the 2017 Contract for Difference (CfD) saw strike prices of £74.75/MWh and £57.50/MWh for delivery year 2021/22 and 2022/23 respectively (a reduction of 38% and 50% respectively compared to the 2015 CfD round) making offshore wind cheaper than new nuclear. Similar trends have occurred in mature European markets, with even the first subsidy free auction bid recorded in Germany. Driving down the cost of foundations, which remains a significant proportion of the overall cost, is a key objective to support continued investment in offshore wind worldwide.

Monopiles are the dominant foundation type, representing 87% of installed foundations at the end of 2017 (Wind Europe, 2018). The loading from the wind on the turbine and waves and currents on the monopile (and transition piece) is predominantly lateral and generates a large overturning moment at mudline. As water depths and turbine sizes increased so did the loading and the sizes of installed monopiles (diameter D and embedment L). The soil-structure interaction is key to the design of monopile foundations yet available guidance in offshore codes and other traditional approaches for modelling the soil response under lateral loading have severe limitations.

The recently completed PISA JIP offers an improved method for the assessment of the soil response. The practical application of the PISA JIP recommendations to the design of a real offshore wind farm is presented and the resulting significant reductions in required embedment depth and monopile mass (with associated fabrication cost and installation risk reductions) are discussed.

## Monopile soil response

### Traditional approaches

Monopiles have traditionally been designed using a Winkler approach with the monopile modelled as a beam supported on non-linear p-y curves representing the relationship between lateral soil reaction and displacement. The p-y formulations presented in the offshore design codes (API, 2011, DNVGL, 2016) have been extensively applied in the oil and gas industry. They originate from limited pile lateral load tests on long slender piles undertaken in the 1950s through to 1970s and are aimed principally at the prevention of collapse.

Their limitations for the design of large diameter rigid monopile foundations governed by consideration of natural frequency and fatigue have been well-documented. Efforts to derive alternative p-y curves for use in monopile design through finite element analyses have been hampered by the lack of pile load tests with representative conditions (L/D ratios and loading type) for calibration. Evidence from monitoring of installed turbines on monopiles (e.g. Kallehave et al., 2012) indicates that the conventional design approaches lead to an under-prediction of the natural frequency (i.e. an under-prediction of the foundation response stiffness).

### PISA approach

The Pile Soil Analysis (PISA) joint industry project was set-up to address the shortcomings of conventional design methods. An overview of the project is presented in Byrne et al. (2017).

The PISA project involved large diameter lateral pile load tests at two sites (Cowden, UK for stiff clay and Dunkirk, France for dense sand), state of the art finite element numerical modelling and the development of a one-dimensional (1-D) design approach using a Winkler-type approach extended to account for four components of soil response. Figure 1 (after Byrne et al., 2017) illustrates the four components of resistance and the associated 1-D soil rection curves:

- p-$v$ curves for lateral soil reaction along the pile embedment
- m-$\psi$ curves for distributed moment along the pile embedment
- $H_B$-$v$ curve for base shear at the pile tip
- $M_B$-$\psi$ curve for base moment at the pile tip

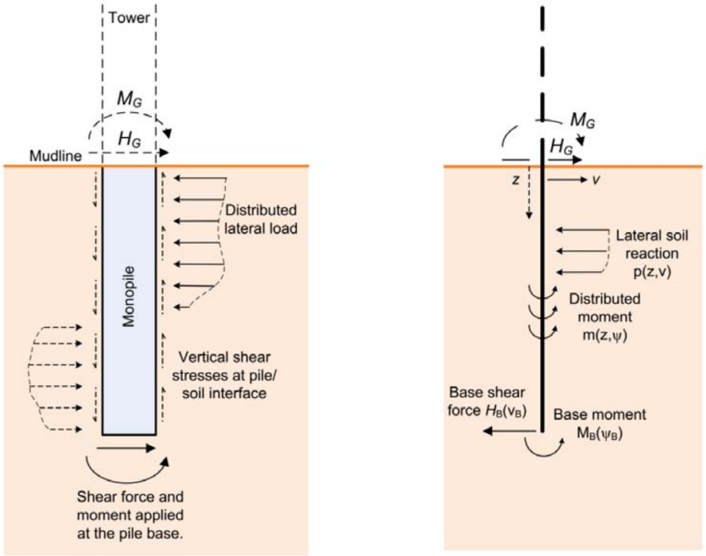


**Figure 1—Components of resistance considered in PISA 1-D formulations (after Byrne et al., 2017)**

The PISA project has defined two design approaches:

- ‘Rule-based’ approach. This uses 1-D soil reaction curves generated using pre-defined mathematical functions with simple soil parameters including undrained shear strength, $s_u$, and small strain shear modulus, $G_0$ for clays and initial vertical effective stress, $\sigma'_{vi}$, and $G_0$ for sands. The formulations of the 1-D soil reaction curves established in the PISA report are based on specific soil profiles (idealised clay till profile and idealised dense sand profile) and a range of monopile geometries and loading regimes. The rule-based method can be adopted for preliminary design activities.
- ‘Numerical-based’ approach. This approach uses 3-D numerical modelling to establish bespoke soil reaction curves (for use in 1-D models) for site specific ground conditions (as well as monopile geometry and loading regime). The numerical-based method can be adopted in detailed analyses.

## Application to real project

### The project

The recommendations from the PISA JIP have been applied in the design of the foundations for a wind farm in the UK North Sea. The wind farm comprises 90 MVOW v164-9.5MW wind turbine generators (WTGs) and two offshore substation platforms (OSPs), all the structures are supported on monopiles. The water depth ranges from 15 to 21m LAT. The ground conditions vary across the site but typically comprise high strength to very high strength overconsolidated clays and dense to very dense sands. The geotechnical properties of the materials were generally comparable to those considered by the PISA JIP at the Cowden and Dunkirk test sites and in the development of formulations for the soil response curves for the 1-D rule-based approach.

## Implementation of PISA recommendations in soil lateral response modelling

The numerical-based approach was used; Figure 2 summarises the process followed to derive 1-D soil lateral response formulations with the following subsections presenting a brief summary of the key steps.

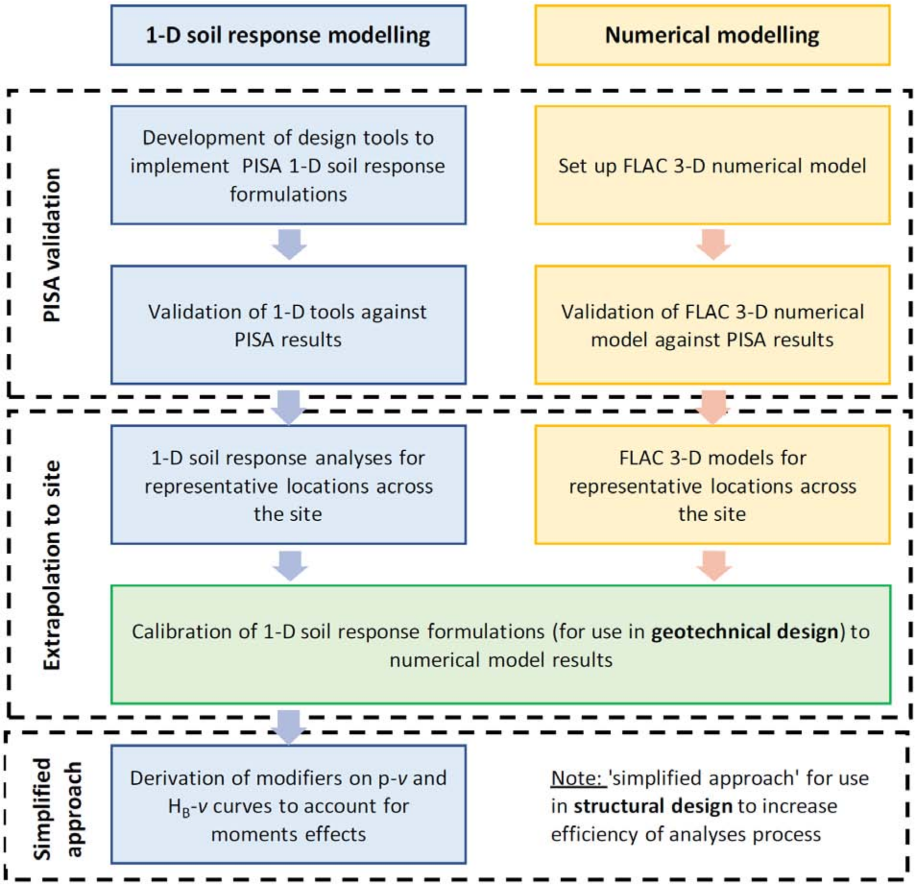


Figure 2—Numerical-based lateral response design method

***PISA validation.***

Tools for 1-D approach

The 1-D assessment of the monopile lateral response was undertaken using the Oasys Alp 19.1 software (hereafter referred to as ALP). Limitations of the software had to be overcome. Firstly, ALP does not allow non-linear $m$-$\psi$ and $M_B$-$\psi$ reaction curves to be modelled directly. To circumvent the issue, the resistances from the $m$-$\psi$ and $M_B$-$\psi$ curves were modelled in ALP as resisting moments. Iterations were required to ensure that the values used corresponded to the predicted rotations (and in sands distributed load level). Secondly, the non-linear $p$-$v$ and $H_B$-$v$ curves could only be defined by six points and iterations were required to ensure the curves discretisation was fine enough around the predicted displacements to limit inaccuracies (as the software interpolates between points).

A tool was developed to generate non-linear soil reaction curves of the form recommended by PISA for all four components of resistance. A second tool, using an application programme interface was developed to automatically import inputs into an ALP model, run ALP, export and interrogate the ALP outputs and iterate with the tool generating the soil reaction curves. Analyses were performed to validate the tools by reproducing results presented in the PISA report as illustrated on Figure 3. Figure 3 presents pile head displacement versus applied horizontal load for a monopile in clay; the plain and dash black lines are results from PISA finite element and 1-D analyses and the red line is the 1-D validation using the tools. The validation analyses confirmed that 1-D models with soil resistance curves of the form recommended by PISA can successfully be implemented in ALP (and other traditional beam element software).

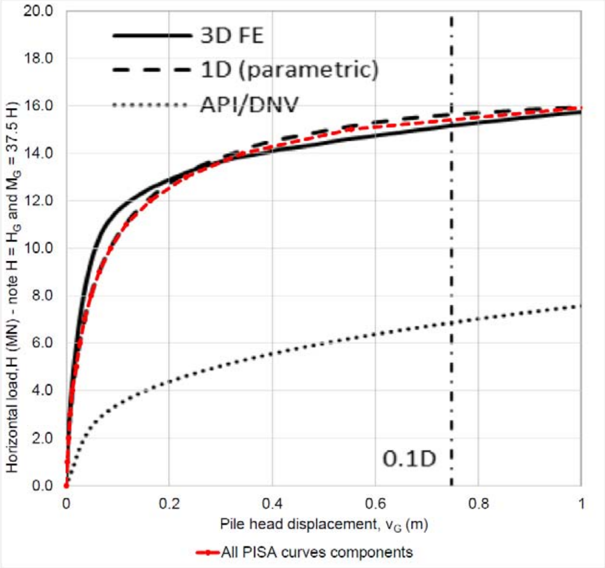


**Figure 3—1-D tool validation (clay)**

## Numerical Modelling

Numerical analyses were performed using the finite difference FLAC3D software version 5.01 (although alternative numerical modelling software could also have been used). The soils were modelled using an isotropic pre-failure non-linear elasto-plastic constitutive law, assuming an associated Tresca failure criterion in clays and a non-associated Mohr-Coulomb failure criterion in sands. In this model the shear modulus degrades with increasing shear strain using a non-linear normalised shear modulus – shear strain relationship applied through a FISH function.

The numerical modelling approach was validated against results presented in the PISA report for finite element analysis of monopiles with geometries comparable to those anticipated for the wind farm.

In clay, the FLAC3D model provided a very good match to the load-displacement response predicted by the PISA numerical modelling work up to load of circa 75% of the failure load (defined as the load causing ground level deflections of 0.1D) as illustrated on Figure 4. This means that the FLAC3D model provided a very good estimate of the monopile response over the loading range under consideration (the factored ULS load was less than 75% of the failure load). For higher load levels, the FLAC3D model overpredicted the stiffness of the response, owing to limitations of the Mohr Coulomb model. In sand the FLAC3D model provided a very good match to the load-displacement response predicted by the PISA numerical modelling work for small displacements and conservatively underpredicted the stiffness of the response at higher load levels.

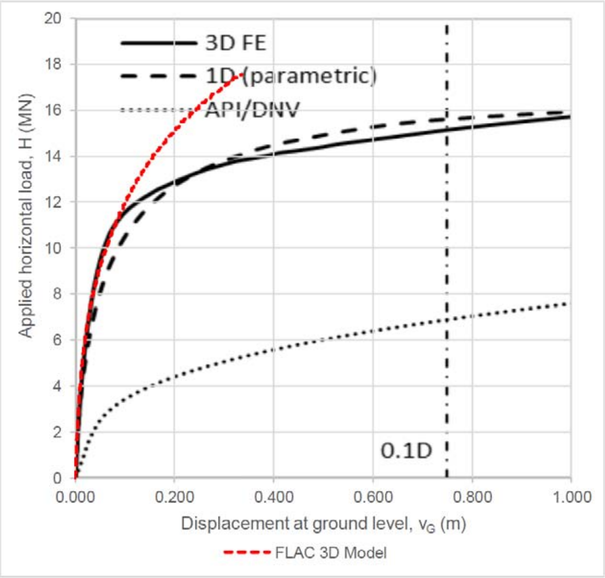


**Figure 4—FLAC3D validation (clay)**

***Extrapolation to site.*** Numerical models were set up in FLAC3D for a limited number of locations deemed to represent the range of ground conditions (in terms of stratigraphy and soil properties) across the site. The load-displacement responses from these numerical models were compared to those predicted in 1-D models considering soil response curves as recommended in the PISA report for the rule-based approach.

Due to the similarity between the idealised soil profiles considered in PISA and the ground conditions across the site, an acceptable match between 1-D soil response analyses and numerical modelling results was obtained. Furthermore, the 1-D models predicted a slightly softer response than the 3-D numerical models which is conservative for design. Therefore, the rule-based PISA soil curves formulations were used directly in design.

***Simplified approach.*** Historically, lateral soil response has been modelled using p-y curves and structural software and analyses processes have been developed to accommodate this simplified representation of the soil-structure interaction. Incorporating non-linear representations of the distributed moment and base moment soil resistance components in structural analyses would require amending the structural analyses processes, amending the input format in structural software and could lead to increased run times. Therefore, for structural analyses, it was advantageous to simplify the soil-structure interaction modelling approach to consider only distributed load and base shear components in analysis models (i.e. essentially only modelling the soil response as non-linear force-displacement springs similar in format to traditional p-y curves).

This simplification was achieved by applying calibrated modifiers on p, $H_B$ and $v$ values to compensate for the contribution to lateral soil response that would have otherwise been modelled by distributed moment and base moment components. Calibration studies were undertaken to select appropriate modifiers to be applied to the p-$v$ and $H_B$-$v$ PISA formulations in sands and clays considering the variability of ground conditions, monopile geometries and loading across the site. These studies involved comparing results of 1-D models that included all four PISA soil response components (‘full PISA’) and of 1-D models that include only p-$v$ and $H_B$-$v$ curves with modifiers (‘simplified PISA’).

For the selected modifiers, the analyses showed that, compared to the full PISA approach, the simplified approach provided a very good match of the monopile displacements at ground level. Up to the factored ULS load the match was found to be excellent. At higher load levels the predicted response was slightly softer (which is conservative for use in design) and the failure load (load for displacements at ground level of 0.1 D) was only slightly underestimated (by up to circa 3%). This is illustrated on Figure 5.

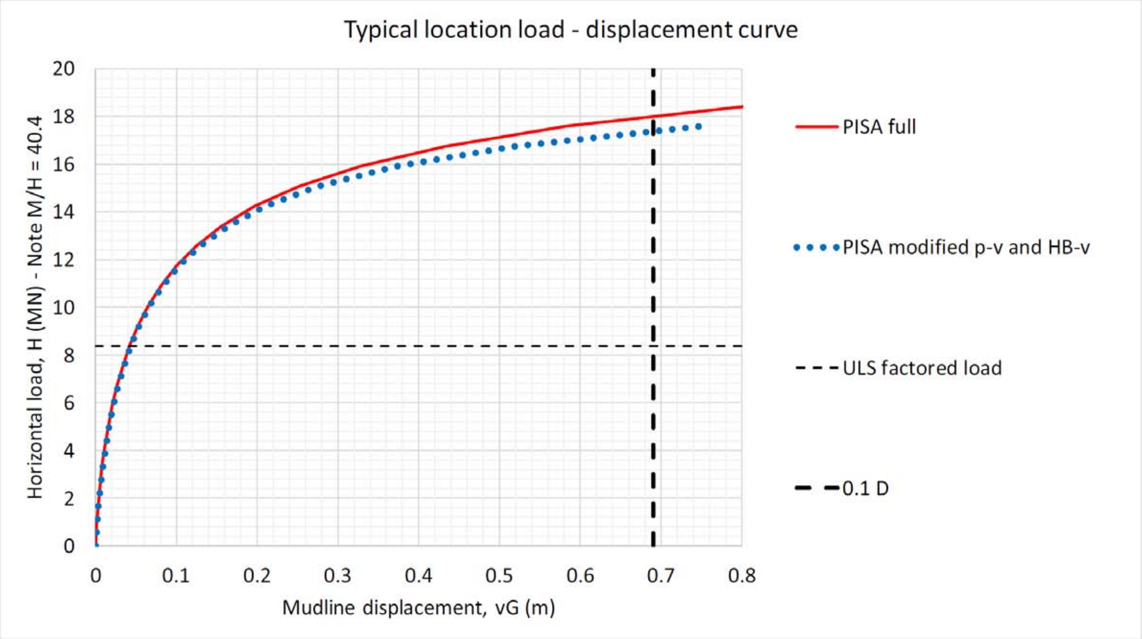
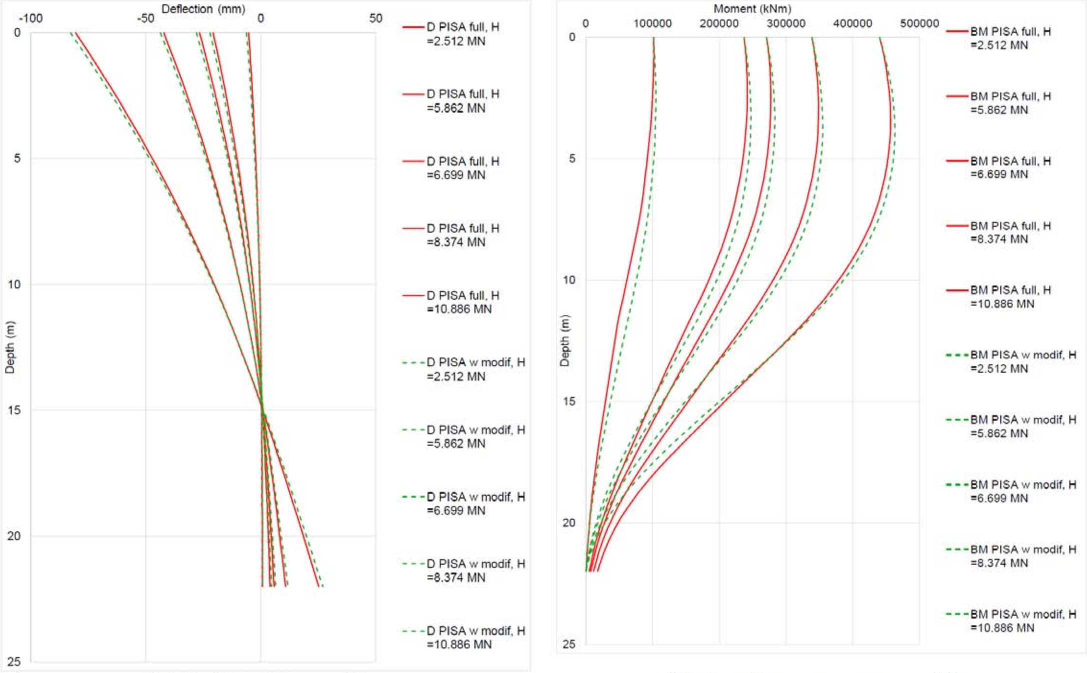


Figure 5—'Full PISA' vs 'Simplified PISA' comparison of load vs ground level deflection response

For the selected modifiers, the analyses showed that, compared to the full PISA approach, the simplified approach provided a very good match of deflections (and rotation) profiles along the monopile as well as a very good match of the bending moment profile along the monopile. The predicted bending moments were slightly higher than those using the full PISA in the upper section of the monopile where they are an important consideration for the structural design and slightly underestimated near the toe of the monopile where they are of little consequence for the structural design. The overestimation of the bending moment in the upper part of the monopile was typically less than 5%. This is illustrated on Figure 6.



(a) Deflection profiles

(b) Bending moment profiles

Figure 6—'Full PISA' vs 'Simplified PISA' comparison of deflection and bending moment profiles

The simplified PISA approach was therefore considered suitable to generate soil springs to the structural analyses software.

## Consideration of cyclic loading

***Insight from PISA tests.*** The PISA recommendations are limited to monotonic loading with only a very limited number of pile load tests having been undertaken under cyclic loading. The limited cyclic testing undertaken as part of PISA nonetheless provided some insight into the performance of short rigid pile under cyclic lateral loading.

The results of one such test, for pile CM5 at the Cowden site, are presented on Figure 7 (after Beuckelaers, 2017) and it can be seen that:

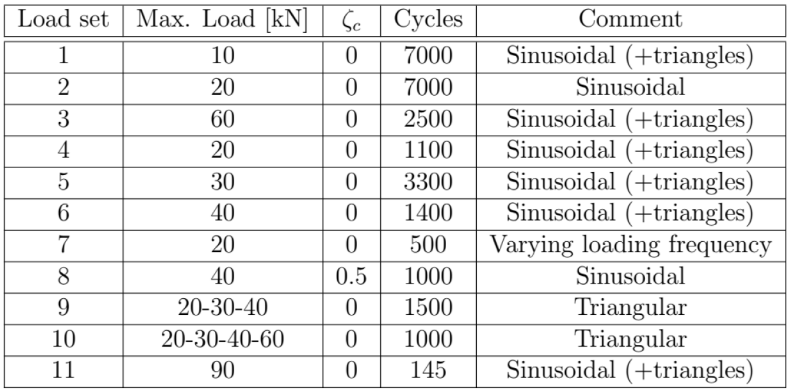
- As the applied load is increased (e.g. from load steps 1 to 3) the stiffness reduces. This reduction in stiffness is not recovered when the cyclic load amplitude is subsequently decreased (i.e. load step 4 has the same amplitude as load step 2 but a lower stiffness as it occurs after the higher amplitude load step 3). It is likely that this response is related to the on-set of gapping which was observed on site. The design included some allowance for gapping in the assessment of the monopiles response.
- For small loads, the accumulated rotation is small and the response is accommodated (e.g. for load steps 1 and 2, accumulated rotations are small and there is no noticeable accumulation of rotation with increasing number of cycles). For higher load amplitudes, the response does not settle into an accommodated pattern (e.g. for load step 3 accumulated rotation increases with increasing number of cycles).

***Geotechnical sizing to limit potential for cyclic degradation.*** Considering the complexities of the behaviour of monopile foundations under cyclic loading and the limited cyclic loading tests data available, a practical approach was used to limit the potential for cyclic degradation and accumulation of rotations.

The geotechnical sizing of the monopile was undertaken to ensure that the majority of the cyclic loading on the monopile over its operational life is sufficiently small (by analogy with the PISA cyclic tests) to ensure a repeated accommodated response with negligible degradation of soil properties and accumulation of rotations.

Numerical analyses in FLAC3D enabled a visualization of the strain levels in the soils under varying load levels and a comparison with the volumetric cyclic threshold shear strain, $_{tv}$, as defined by Vucetic (1994) below which the soil would be expected to remain practically non-degradable. These suggested that for small applied loads representative of the anticipated FLS load level the soil would be expected to remain practically non-degradable and that for all but a very few cycles during a storm event, the soil response in the bottom third of the monopile would not degrade.

Table 3.4: Cyclic loading routine for CM5.



| Load set | Max. Load [kN] | $\zeta_c$ | Cycles | Comment |
|---|---|---|---|---|
| 1 | 10 | 0 | 7000 | Sinusoidal (+triangles) |
| 2 | 20 | 0 | 7000 | Sinusoidal |
| 3 | 60 | 0 | 2500 | Sinusoidal (+triangles) |
| 4 | 20 | 0 | 1100 | Sinusoidal (+triangles) |
| 5 | 30 | 0 | 3300 | Sinusoidal (+triangles) |
| 6 | 40 | 0 | 1400 | Sinusoidal (+triangles) |
| 7 | 20 | 0 | 500 | Varying loading frequency |
| 8 | 40 | 0.5 | 1000 | Sinusoidal |
| 9 | 20-30-40 | 0 | 1500 | Triangular |
| 10 | 20-30-40-60 | 0 | 1000 | Triangular |
| 11 | 90 | 0 | 145 | Sinusoidal (+triangles) |

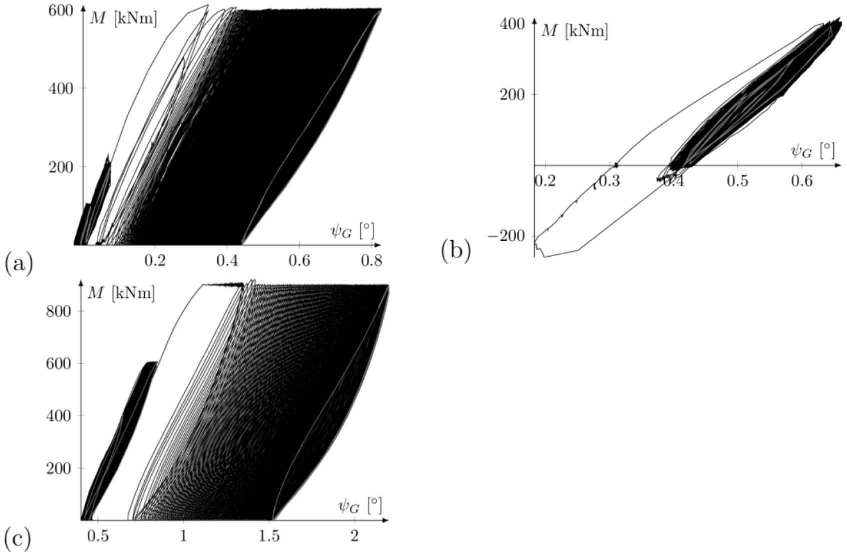


Figure 3.20: Moment-rotation response of CM5 for load sets (a) 1 to 3, (b) 4 to 8 and (c) 9 to 11.

**Figure 7—CM5 cyclic testing (after Beuckelaers, 2017)**

## Outcomes

The tools to implement the soil reaction curves of the form recommended by PISA in 1-D models were further automated to consider varying embedments. This enabled the fast generation of graphical outputs to facilitate decision making with regards to selecting embedment. An example of such outputs is presented on Figure 8.

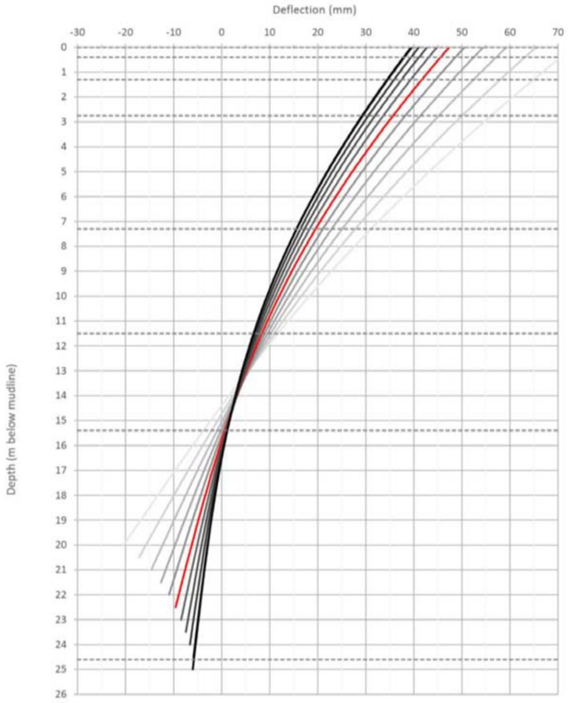


Figure 8—Illustration of automated outputs deflection profile under SLS load for varying embedement

The implementations of improved soil response modelling based on the PISA JIP recommendations has led to a reduction of monopile embedment of 1 to 2 diameters compared to conventional design approaches based on historical p-y curves formulations. This significant reduction of embedment, combined with a refined assessment of wave loading considering bi-directional bi-modal wave loading, has led to light monopiles. This is illustrated on Figure 9 which presents the relationship between hub height above mudline and monopile mass. The light blue dots represent the smallest, largest and average hub heights for the wind farm and it can be seen that these indicate a significant mass reduction compared to the trend of historical monopile foundations. Compared to the trend, the mass saving for the average hub height on the site is in excess of 30%.

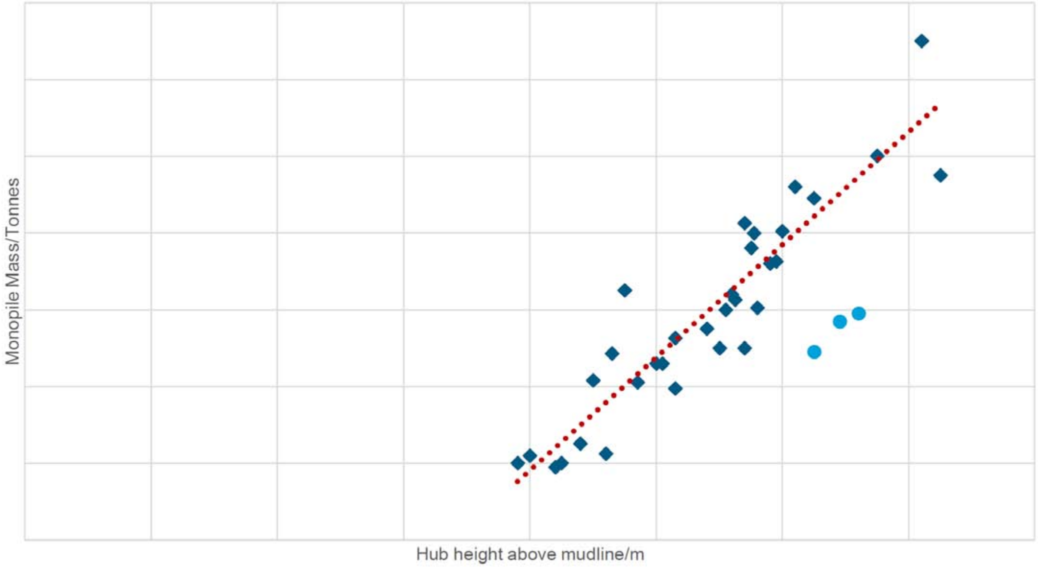


Figure 9—Monopile mass vs hub height above mudline – PISA design compared to trend based on traditional approaches

In addition to the monopile mass savings discussed above, the reduced monopile penetrations also lead to reduced installation times, reduced installation risks, reduced fatigue during driving (which leads to reduced mass) and reduced environmental impact (noise).

## Conclusions

Whilst monopiles have been the dominant foundation type for offshore wind, the soil response which plays such a significant role in their design has historically been modelled using either inadequate or poorly calibrated representations. The recently completed PISA JIP which involved large scale lateral pile load tests at two sites and state of the art finite element analysis offers recommendations to better model the soil response. It considers four components of resistance and recommends that formulations for the non-linear soil reaction springs be derived from 3-D numerical models (calibrated to pile load test results).

The PISA JIP recommendations have successfully been implemented for the design of an offshore wind farm in the UK North Sea and some of the practical aspects of the implementation have been presented. The improved soil response modelling has resulted in significant monopile embedment reductions (1 to 2 D) and mass reductions (in excess of 30%) compared to traditional design approaches.

The implementation of the PISA JIP improved soil response modelling approach leads to signifcant CAPEX reductions and also enables monopiles to be considered in deeper waters and for larger turbines than previously considered. Further work is required in the modelling of soil response under cyclic loading (which would benefit from benchmarking to monitor performance of installed offshore wind turbines) with the potential for further cost reductions.

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